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Interface analysis on MOVPE grown InP–GaInAs–InP double heterostructures for application in infrared solar cells

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ABSTRACT

We investigate the $Ga_{0.47}In_{0.53}As$ to InP interface with respect to their charge carrier lifetimes, interface recombination velocity and lateral interface homogeneity by using a time- and spatially resolved photoluminescence technique. Different preparation routes, such as group-III- and group-V-rich variations for the upper $Ga_{0.47}In_{0.53}As$ to InP interface, which is basic for optoelectronic and photovoltaic applications, are presented for a series of so-called double heterostructures with different absorber thickness. For chosen interface preparation routes the bulk lifetime and interface recombination velocity at a fixed excitation density are extracted. Overall low interface recombination velocities occur, while one group-III-rich preparation route with an enhanced lateral homogeneity results in higher lifetimes at all excitation densities compared to the sophisticated group-V-rich preparation.

1. Introduction

III-V-GaInP/GaInAs/GaAs-triple junction solar cells are reaching conversion efficiencies of around 41.6% under concentrated sunlight illumination to date [1,2] and are industry standard for space and nowadays also for terrestrial applications [3–5], but they are reaching their practical limit [6]. Research is focusing towards multijunction solar cells involving four or more subcells. Beside that also material quality and the choice of bandgap energies determine the resulting performance of solar cells, exactly the overall conversion efficiency. Introduction of a subcell absorber material with a band gap energy of around 1 eV promises higher efficiencies at theoretically calculated ideal bandgap configuration [4,5]. At the lattice constant of Ge this can only be realized with diluted nitride semiconductors like GaInNAs [7], but these materials often suffer on insufficient quality, when they were grown by metal organic vapor phase epitaxy. Another option is the use of metamorphic subcell configurations. Here lattice mismatched subcells are combined by using buffer layers to relax the lattice strain. These structures cannot be dislocation free and therefore device performance is reduced.

Direct wafer bonding is one opportunity to combine materials with different lattice parameters through an electrically conductive, permanent and optically transparent layer. Thus, the use of an InP based $Ga_{0.21}In_{0.79}As_{0.45}P_{0.55}/Ga_{0.47}In_{0.53}As$ low bandgap tandem cell [8] becomes attractive to replace the Ge bottom cell from a common 3-junction solar cell to create a four junction solar cell with nearly optimal bandgap combination [6,9,10].

Recently such a four junction solar cell could be realized in cooperation with the Fraunhofer-Institute for Solar Energy Systems (ISE), the Soitec Company, the Helmholtz-Center Berlin (now Photovoltaics Group at TU Ilmenau) and the French research institute CEA-leti by wafer bonding reaching an efficiency of 44.7% at 298 suns [11]. This efficiency could be increased to 46.0% at 508 suns nowadays [12]. Herein the InP based GaInAsP/GaInAs dual junction is used as bottom-tandem cell in combination with a GaAs based GaInP/GaAs top-tandem cell. Since theoretically conversion efficiencies of these nearly optimal bandgap combinations lying above 60% practical conversion efficiencies in the range of 50% appear to be feasible [13].

As mentioned before one of our main research fields is focusing on growth and analysis of monolithic $Ga_{0.21}In_{0.79}As_{0.45}P_{0.55}/Ga_{0.47}In_{0.53}As$ tandem cell. As one key material parameter that can a priori determine the potential solar cell performance and thus the minority charge carrier lifetime is the diffusion length, we apply time resolved photoluminescence (TRPL) as a suitable non-destructive method to analyze the electronic quality of the epitaxial grown GaInAs-absorber layer and especially the GaInAs to InP interface formation, which is crucial for the tandem solar cell structure and is known to be difficulty to grown [14,15]. This

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interface is also known to be more critically than the inverted InP to GaInAs interface. Many studies have demonstrated that the InP to GaInAs interface is much more abrupt than the GaInAs to InP interface [14,16–18] and Refs. therein.

To address the absorber layer and interface directly and to separate the electron hole recombination of the bulk from that of interfaces, specially designed so called "double heterostructures (DH-structures)" were used. These structures contain a $Ga_{0.47}In_{0.53}As$ absorber layer embedded between two thin InP barrier/confinement layers. So the DH-structure contains both interface transitions. By varying only the preparation of one of them, it becomes possible to distinguish between both and to evaluate the influence of their preparation.

Here we reveal the lifetimes for different preparation routes of the upper GaInAs to InP interface for a series of different thick DH-structures (see Fig. 1).

2. Experimental

The epitaxial growth of DH-structures was performed in a modified, horizontal Aixtron AIX-200 metal organic vapor phase epitaxy (MOVPE) reactor with dedicated UHV-transfer system comprising a specially designed sample holder system without sample rotation [19].

DH-structures with $Ga_{0.47}In_{0.53}As$ layers embedded between two 30 nm thick InP barriers were grown each on a quarter of a two inch p-doped InP(100) 2° B < 111 > substrate. The active GaInAs layer thickness within these DH-structures was varied (1000 nm , 500 nm , 250 nm , 100 nm and 50 nm) to separate the influence of the interface recombination from the bulk lifetime. For all layer thickness variations different growth strategies of the interface preparation were applied as described below (see also Table 1). Trimethylindium (TMIn), triethylgallium (TEGa), tertiarybutylarsine (TBAs) and tertiarybutylphosphine (TBP) were employed as III–V precursors and diethylzinc (DEZn) for p-type doping. The growth temperature was 600 °C and the doping level of approximately 1×10^{17} cm^{-3} was adjusted during growth of the entire layer structure.

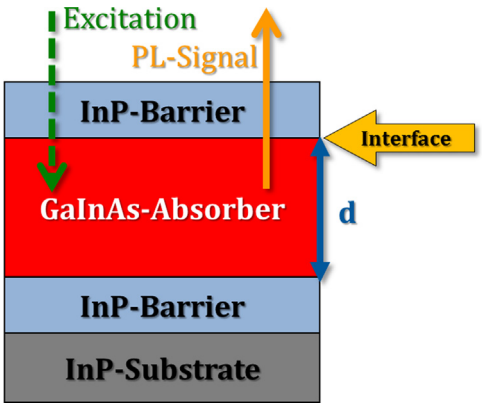

Fig. 1. DH-structure design, the critical interface is highlighted.

Table 1
Gas switching sequences.

Preparation route	Time t_1 [s]	Time t_2 [s]	Coverage [mono layer]
A	4	0	0
B	10	1.5	1.6
C	60	3	3.3
D	30	3	3.3
E	10	3	3.3

After the InP buffer growth the first heterointerface, i.e. the lower InP to GaInAs interface, was prepared on the well-established route, where the surface was constantly stabilized by means of group-V-precursor partial pressure, either TBP or TBAs, respectively [20,21], during the growth stop, when switching between the different layers, followed by the lattice matched GaInAs absorber layer growth. The upper GaInAs to InP interface is predicted to be more complicated to prepare. The main problem seems to be the so called "carry-over" of arsenic from the absorber layer into the upper InP layer, which causes a blurred and strained region of some monolayers height with escalated defect density resulting in a decreased minority carrier lifetime. In Refs. [22,23] it was already shown that a so-called 'group-III rich' interface preparation can reduce the carry-over of arsenic into the upper layer.

Herein a sharper GaInAs/GaAsSb interface would be achieved, if the growth of the GaAsSb layer was performed on the group-III-rich GaInAs surface. Hence, this method was transferred to the second heterointerface of DH-structure grown here, the upper GaInAs to InP interface. This interface was prepared 'group-III-rich' in four different ways to find out the most favorable one. Therefore the GaInAs layer growth was finished by stabilizing the GaInAs interface during the growth stop to the following InP layer with TBAs supply for time t_1, respectively.

Thereafter, a purge of the both group-III components (TMIn and TEGa) was performed together for time t_2 followed by the direct growth start of the InP cap layer with 30 nm thickness (see Fig. 2).

This purge sequence is supposed to prevent the arsenic "carry-over" in the InP layer. Time t_1 and t_2 were varied to find the most favorable sequence for a sharp interface formation (see Table 1 for switching sequences). All these 'group-III-rich' preparation routines (named ***B–E***) were compared with a 'group-V rich' preparation routine (named ***A***), without any post-flow (t_2) of the group-III components. The temporal decay of the radiative recombination, i.e. the infrared band-to-band photoluminescence after excitation with a short light pulse (using a 640 nm pulsed diode laser (PicoQuant)), was measured spatially resolved with a time correlated single photon counting (TCSPC, PicoHarp 300 (PicoQuant)) [8,24].

The excitation density was calculated with respect to the effective sample absorption, repetition rate, laser power and the pulse profile (FWHM) at the sample position using a photodiode directly below the sample. The photoluminescence signal was detected using an extended GaInAs photomultiplier tube (PMT). The overall time resolution of the system was in the range of 300–600 ps dependent on excitation intensity, but far below the detected lifetimes.

3. Results and discussion

The lifetime of minority charge carriers (here electrons) in lattice-matched InP/$Ga_{0.47}In_{0.53}As$/InP DH-structures (see Fig. 1) was measured to evaluate the impact of different interface formations on the lifetime and to discover the most favorable

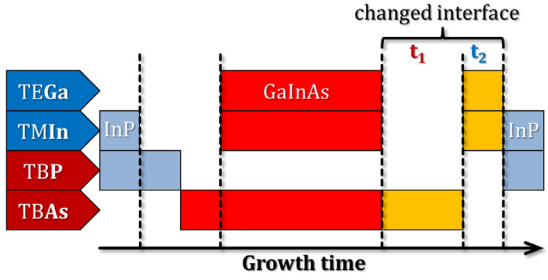

Fig. 2. Gas switching sequences used for MOVPE grown DH-structures.